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13. ABSTRACT (Maximum 200 words) The Center for Quantum Information (CQI) is a multidisciplinary research center for the study of the processing and transmittal of information using quantum systems. The major goals of the center are to develop a toolbox of quantum procedures and protocols in a variety of elementary systems, ranging from atoms and molecules to photons and electronic nanostructures, and to formulate the elements of a quantum theory of information. To achieve these aims, CQI is based upon the interaction of several highly interdisciplinary research projects. The Center is a collaborative effort of nine professors from five universities (Rochester, Harvard, Stanford, Cornell, and Rutgers). Expertise ranges from quantum optics and atomic physics, through mesoscopic electronics, to information theory and its applications in commercial optical telecommunications systems.			
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University of Rochester
Rutgers University
Stanford University

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ARO-MURI Center for Quantum Information

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Section 1: Foreword

The Rochester-Stanford Center for Quantum Information MURI was funded in response to the Fiscal Year 1999 DoD Multidisciplinary Research Program of the University Research Initiative BAA which was authored by Michael Foster of AFOSR and Louis Lome of BMDO. It was set up with the intent of getting the experts in classical information theory and those in quantum control, quantum devices, and quantum optics talking to each other and indeed working together to develop the foundations of the new field of *quantum information*. Two strong proposals were received in the original solicitation and it was decided to divide the available funds between two Centers; one based in Stanford University directed by Professor Charles Marcus and including also Professors Yoshi Yamamoto, Thomas Cover, and Martin Morf of Stanford as well as Professor Michael Gershenson of Rutgers. The second Center was based at the University of Rochester and directed by Professor Ian Walmsley. This Center also included Professors Joseph Eberly, Carlos Stroud, and Edward Titlebaum from Rochester as well as Professor Toby Berger of Cornell University. A non-funded collaboration with Dr. Richart Slusher's group and Lucent's Bell Laboratories was also a part of the Rochester Center. With the reduced funding of each of the individual centers the individual efforts were reduced somewhat in scope from the original proposals with only these core members retained. At the same time the project goals were reformulated at a kickoff meeting to be the development of a *Quantum Toolbox* of devices, algorithms, and approaches to quantum information processing across a wide range of platforms. These revised project goals are described in more detail in Section 2 below.

After the program had been underway for less than two years it was again reorganized when Professor Marcus accepted a new position at Harvard University and soon thereafter Professor Walmsley accepted a position at Oxford University. The administration of the two Centers was combined and directed by a new PI, Professor Carlos Stroud of the University of Rochester. Also, Professor Titelbaum was dropped from the program at Rochester and Professor Nicholas Bigelow was added.

In spite of the numerous changes in the program it was quite successful in meeting its modified goal of developing a Quantum Toolbox, at publishing a large number of refereed publications in the most prestigious journals, educating students who are already beginning to take up important positions in the strategically important new field, and organizing interdisciplinary workshops and meetings of the sort envisioned in the original BAA.

Section 2: Statement of the Problem Studied

As described earlier in the Foreword, Section 1, the goal of this MURI Center changed from the original BAA to the final reconfigured combined Center. The goal as defined at the kickoff meeting held at ARL was to develop a *toolbox for quantum information.* Specifically the toolbox was to consist of a set of tools that allowed the common study of the problems of decoherence, entanglement, fidelity and resources to be discussed and attacked in the separate disciplines of mesoscopic electronics, AMO physics, information theory, and communications *outside of the field of quantum computing.*. A second goal was to foster communication between researchers in classical information theory and those in quantum optics. A third goal was to educate a new generation of students proficient in the new hybrid field of quantum information. It was further stated at that meeting by Dr. Henry Everitt of ARO that he would expect at least one ``home run", *i.e.,* very important research advance, to come out of the Center.

The proscription to "outside the field of quantum computing" was rather unusual, but it was to note that there were other centers with support devoted specifically to quantum computing and that this center was to be more broadly directed to other applications of quantum information.

Section 3: Summary of the Most Important Results

The most important results are contained in the 139 refereed publications including 51 in the most prestigious journals. The work was also presented in more than 142 conference presentations. These are listed in Section 4.

A primary task was to develop tools for the Quantum Information Toolbox. A large number of these tools were developed. We will highlight some of them here.

Several offered the possibility of new scalable solid-state platforms for information processing:

- **Fabrication of new semiconductor platform for quantum information - Charles Marcus:** Quantum dots from GaAs were fabricated and spin transport was studied. Two particle entanglement was observed in these devices.

- **Electron-electron interaction demonstrated in zero- and one-dimensional systems - Yoshihisa Yamamoto:** Quantum Hanbury Brown-Twiss measurements were observed in quantum dots and quantum wires.

- **Ultra-small Josephson junctions fabricated for qubits - Michael Gershenson:** Magnetic field will break the symmetry to produce symmetry-based qubits.

Others extend the tools of classical information theory into the quantum domain.

- **Quantum Rate-Distortion Theory for I.I.D - I. Devtek and T. Berger:** Rate distortion theory is applied to quantum information.

- **Duality between Channel Capacity and Rate Distortion with Two-Sided State Information - Thomas Cover:** The duality between channel capacity and data compression is demonstrated for the case when the state information is available to the sender, the receiver or both.

Some new quantum properties were found that apply to a range of platforms.

- **Force of Entanglement -J. H. Eberly:** It is demonstrated that just as wave function symmetrization for spin statistics can lead to an effective exchange force there is an effective force associated with entanglement.

- **Multivalued logic gates for quantum computation - A Muthukrishnan and C. Stroud:** A universal gate is demonstrated for multilevel quantum logic.

Some AMO-type platforms were demonstrated for quantum information.

- **Entanglement of a gas of atomic spins - N. Bigelow:** Entanglement of macroscopic cells of spin polarized alkali vapors was demonstrated.

- **Single pixel excitation of a three-dimensional electron wave packet demonstrated - C. Stroud:** A three-dimensionally localized Rydberg electron wave packet was created and controlled using THz half-cycle pulses.

- **Generation of correlated photons in controlled spatial modes by down-conversion in nonlinear waveguides - I. Walmsley:** A new efficient technique of generating biphotons was demonstrated.

This is a small sampling of the fifty or more new quantum information tools that were developed through the work in this MURI. Any attempt at a complete listing would be redundant of the abstracts of the refereed publications that are contained in Section 4.a.

A secondary goal of this Center was to foster interaction between those working in classical information theory and those working on quantum devices and quantum optics. This effort was hampered by the large geographical spread of the participants from Stanford to Harvard, and even in the last two years Oxford, and the dilution of the budget over nine separate faculty groups. This left minimal funds for travel and coordination, however there were some significant successes. First, a very successful international conference was sponsored: the First International Conference on Quantum Information. It was held in Rochester in June 2001 and attracted more than 200 participants. The range of speakers was particularly impressive ranging over experts in both classical and quantum information and the whole range of possible platforms. The proceedings were released in CD form by the Optical Society of American in their TOPS series. The second in the series of conferences was held in Oxford University, and the third meeting in the series is in its early stages of planning as a satellite to the next Rochester Conference on Coherence and Quantum Optics in 2007.

In addition to this series of international conferences several smaller workshops were held, some in conjunction with the annual reviews, and others separately. Long-term international visitors to the Center included Professor Stig Stenholm from the Royal Institute of Technology in Stockholm, Sweden, and Kazimir Rzawewski from the Polish Academy of Sciences in Warsaw. There were regular seminars in Rochester which included participation by the classical information theory group from Cornell as well as the AMO group in Rochester. Notably, this led to a collaborative project which resulted in a joint publication of the two groups. Dr. Igor Devtek who completed his doctoral dissertation working with Professor Berger at Cornell went on to continue his work straddling the boundary between classical and quantum information theory with Bennett's group at IBM. Devtek has more recently taken a faculty position at which he can continue to pursue his research in this area.

Other notable accomplishments in integrating classical and quantum information were the development of a new popular cross-disciplinary course in classical and quantum information at Stanford University, and the development of a new undergraduate laboratory course in quantum information at the University of Rochester.

Section 4: Publications

Section 4.1: Papers Published

Condensed Matter Projects

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61. "Generation of Pure-State Single-Photon Wavepackets by Contitional Preparation Based on Spontaneous Parametric Downconverstion," A. B. U'Ren, C. Silberhorn, K. Banaszek, I. A. Walmsley, R. Erdmann, W. P. Grice, and M. G. Raymer, Laser Physics 15, 146 (2005).

Section 4.2: Manuscripts Submitted But Not Published

Condensed Matter Projects

1. "Duality between channel capacity and rate distortion with state information and the Wyner-Ziv formula," T. Yamamoto, to appear in a special issue on Shannon theory, IEEE Transactions on Information Theory, April 2002.

2. "Multiple reflection effects in an electron beam splitter device," M. Aranzana, W.D. Oliver, G. Feve, N.Y. Kim, submitted to Physical Review B (2002).

Information Theory Projects

1. "NanoArchitectures – Comparing and Contrasting Biological and Computer Systems," S. Barbu, M. Morf, invited chapter in book on "Nanobiology: Nanoscale Fabrication of a New Generation of Biomedical Devices," Ralph S. Greco, M.D., Jan. 2004.

2. "The Capacity of Finite-State Channels with Feedback," J. Chen and T. Berger, preprint, School of ECE, Cornell University, Ithaca, NY 14850, August 2003.

3. "The capacity of a quantum channel for simultaneous transmission of classical and quantum information," I. Devetak, P. W. Shor, preprint quant-ph/0311131(2004). To appear in Comm. Math. Phys.

4. "Distilling common randomness from bipartite quantum states," I. Devetak and A. Winter, preprint quant-ph/0304196 (2004). To appear in IEEE Trans. Inform. Theory.

5. "The union of physics and information," I. Devetak and A. E. Staples, preprint quant-ph/0112166 (2002).

6. "Capacity theorems for quantum multiple access channels. Part I: Classical-Quantum and Quantum-Quantum Capacity Regions," J. Yard, I. Devetak, and P. Hayden, quant-ph/0501045, submitted to IEEE Trans. Inf. Theory.

7. "Classical capacity of quantum binary adder channels," G. Klimovitch, A. Winter, in preparation.

8. "Classical capacity of quantum channels with two-sided state information," I. Devetak, J. Yard, in preparation.

9. "Clockless logic design and the zero energy hypothesis," S. Barbu, M. Morf, to be submitted to International Conference on Circuits and Systems, 2004.

10. "Flow Extensions of classical nonlinear stochastic systems and information theory to quantum systems," S. Barbu, Ph.D. thesis expected July 2004.

11. "Quantum channels with state information," I. Devetak and J. Yard, in preparation.

12. "Quantum Reverse Shannon Theorem," C. H. Bennett, I. Devetak, P. W. Shor, and A. Winter, in preparation.

13. "Simultaneous classical-quantum capacities of quantum multiple access channels," J. Yard, Ph.D. thesis, expected March 2005.

Quantum Optics Projects

1. “Compressible vortex matter,” L. Baksmaty, S. Woo, S. Choi, and N. P. Bigelow, Nature, in review.

2. “Dynamics of vortex lattices: from the hydrodynamic to the quantum Hall regimes,” L. Baksmaty, S. J. Woo, S. Choi and N. P. Bigelow, Phys. Rev. Lett., in review.

3. “An example of quantum control via Feshbach resonance in Bose-Einstein condensates,” S. Choi and N. P. Bigelow, Phys. Rev. A, Brief Reports, in review.

4. “Experimental phase-sensitive cloning,” John C. Howell, Irfan A. Khan, D. Bouwmeester, and N. P. Bigelow, Phys. Rev. Lett., in review.

5. “Two-dimensional matrix continued fraction and the time-independent Schrödinger equation,” H. Y. Ling, J. Michaelson, H. Pu, L. Baksmaty, and N. P. Bigelow, J. Comp. Phys., accepted.

6. “Vortex Matter in an Optical Lattice,” H. Pu, L. Baksmaty, S. Yi, N. P. Bigelow, Phys. Rev. Lett. in review.

7. "Reverse decoherence and photon wave functions", J.H. Eberly, K.W. Chan and C.K. Law, invited article in Chaos, Solitons and Fractals (to be submitted).

8. “Schmidt-mode analysis of entanglement for quantum information studies,” J. H. Eberly, in Proc. of NATO-ASI on Quantum Communication and Information Technologies, edited by A. Shumovsky (Springer-Verlag, 2003).

9. “Atomic wave packet basis for quantum information,” A. Muthukrishnan and C. R. Stroud, Jr., to appear Phys. Rev. A (2004).

10. “Quantum interference and coherent wave mixing,” Vincent Wong, Ryan S. Bennink, Alberto Marino, Robert W. Boyd, and C. R. Stroud, Jr., submitted to Phys. Rev. A (2004).

11. “Conditional preparation of single photons for scalable quantum-optical networking,” A. U'Ren, Ch. Silberhorn, K. Banaszek and I. A. Walmsley, submitted to Phys. Rev., December 2003.

12. “Time-multiplexed photon-number resolving detector” D. Achilles, Ch. Silberhorn, C. Sliwa, K. Banaszek, I. A. Walmsley, M. Fitch, T. Pittman, B. C. Jacobs and J. Franson, to appear in J. Mod. Opt., (2004).

13. “Photon engineering for quantum information processing,” A. U'Ren, K. Banaszek and I. A. Walmsley, to appear Quantum Information and Computation (invited paper), 2003.

14. “Generation of pure single photon wavepackets by conditional preparation based on spontaneous parametric down conversion,” A. B. U’Ren, Ch. Silberhorn, R. Erdmann , K. Banaszek ,W. P. Grice, and I. A. Walmsley, submitted to Laser Physics, (2004) (invited paper).

15. “Quantum interference and coherent wave mixing,” Vincent Wong, Ryan S. Bennink, Alberto Marino, Robert W. Boyd, and C. R. Stroud, Jr., submitted to Phys. Rev. A (2004).

Section 4.3: Papers Presented at Meetings

Condensed Matter Projects

1. "The crossover from weak to strong localization and hopping conductivity in conductors with a large localization length", M. Gershenson, Workshop on Physics of Ultrathin Films Near the Metal-Insulator Transition, Brown University, December 1999.

2. "Quantum indistinguishability in two-dimensional electron gas systems," Y. Yamamoto, R. Liu, W. Oliver, J. Kim, and X. Maitre, Proceedings of 15th International Symposium on Advanced Physical Fields, pp. 417-426, March 2000.

3. "Hot-electron detectors: toward record sensitivity via controllable electron-phonon coupling", M. Gershenson, 11th Int. Symposium on Space Terahertz Technology, May 2000.

4. "Hopping with a large localization length in low-dimensional conductors", M. Gershenson, Int. Conference "Meso-2000", Chernogolovka, July 2000.

5. "Electron-phonon interaction in low-dimensional systems: old puzzles and new applications", M. Gershenson, Workshop on Quantum Transport and Mesoscopic Physics, Taiwan, January 2001.

6. "Measurements of the effective g-factor and mass of electrons in Si MOSFETs over a wide range of carrier densities", M. Gershenson, The APS March Meeting, Seattle, March 2001.

7. "Crossed magnetic field technique for studying spin and orbital properties of 2D electrons in the dilute regime", M. Gershenson, the 14th Int. Conf. On Electronic Properties of Two-dimensional systems, Prague, July 2001.

8. "Interaction effects in conductivity of Si MOSFETs at intermediate temperatures," Michael Gershenson, Invited, NEC Research Workshop on 2D MIT, May 2002.

9. "Interaction Effects in Electron Transport in Si Inversion Layers at Intermediate Temperatures," Michael Gershenson, Invited, Int. Conference on Localization and Interaction Effects in Disordered Solids (Localization-02), Kyoto, August 2002.

10. "Interaction Effects in Conductivity of High-Mobility Si MOSFETs at Intermediate Temperatures," Michael Gershenson, Invited, Brown University, November 2002.

11. "Single-Crystal Organic Field Effect Transistors," M.E. Gershenson, NATO Advanced Research Workshop "Coherent Charge and Spin Transport on a Nanoscale", Chernogolovka, Russia, June 2003.

12. "High-Mobility Single-Crystal Organic Transistors," M.E. Gershenson, Int. Workshop on Electronic Properties of Organic Conductors, Leiden, July 2003.

13. "Interaction Effects in the Conductivity of Si Inversion Layers in the Dilute Regime," M.E. Gershenson, the Aspen Summer Workshop "Interactions and Disorder in Metals and Insulators in Two Dimensions", August 2003.

14. “Nonlinear differential conductance and Shot Noise Suppression in a GaAs Quantum Point Contact,” N.Y. Kim, Y. Yamamoto, Y. Hirayama, Poster Presentation, Stanford-ENS Symposium on Quantum Entanglement, December 2003.

15. “High-mobility FETs based on single crystals of organic molecular materials,” M.E. Gershenson, DOE Workshop on the field effect measurements of transport in condensed matter systems, Santa Fe, January 2004.

16. “Fermi liquid renormalizations of low density electrons in silicon MOSFETs,” M.E. Gershenson, The APS March Meeting, Montreal, March 2004.

17. “Intrinsic Charge Carrier Transport on the Surface of Organic Semiconductors,” V. Podzorov, invited talk, 2004 Electronic materials Conference (EMC), Notre Dame University, Notre Dame, Indiana, June 23-25, 2004,

18. “Interaction Effects in High-Mobility Si MOSFETs,” M. Gershenson, invited talk at the Workshop on Novel States and Phase Transitions in Highly Correlated Matter, Trieste, July 2004.

Information Theory Projects

1. “Duality and a proof of capacity for a class of channels with state information,” M. Chiang and T. Cover, Proceedings of IEEE International Symposium on Information Theory and Applications, Honolulu, Hawaii, November 2000.

2. “Parallel Gaussian feedback channel capacity,” M. Chiang and T. Cover, Proceedings of IEEE International Symposium on Information Theory and Applications, Honolulu, Hawaii, November 2000.

3. “Channel capacity and state estimation,” M. Chiang, A. Sutivong and T. Cover, Proceedings of the IEEE International Symposium on Information Theory and Applications, pp.838-840, Honolulu, Hawaii, November 2000.

4. “Quantum rate-distortion theory,” I. Devetak and T. Berger, poster presentation, QIP2001, 4th Workshop on Quantum Information Processing, Amsterdam, January 2001.

5. “Low-entanglement remote state preparation,” I. Devetak and T. Berger, contributed talk, International Conference on Quantum Information, Rochester, NY, June 13-16, 2001.

6. “Quantum rate-distortion theory for I.I.D. sources,” I. Devetak and T. Berger, contributed talk, 2001 IEEE International Symposium on Information Theory, Washington, DC, June 26-July 1, 2001.

7. “Writing on colored paper," W. Yu, A. Sutivong, D. Julian, T. Cover and M. Chiang, Proceedings of IEEE International Symposium on Information Theory, Washington, D.C., June 2001.

8. “On the classical capacity of a quantum multiple-access channel,” G. Klimovich, Proceedings of the IEEE International Symposium on Information Theory, Washington, D.C., June 2001.

9. “Unified duality of channel capacity and rate distortion with state information,” M. Chiang and T. Cover, Proceedings of the IEEE International Symposium on Information Theory, Washington, D.C., June 2001.

10. “Tradeoff between message and state information rates,” A. Sutivong, T. Cover and M. Chiang, Proceedings of the IEEE International Symposium on Information Theory, Washington, D.C., June 2001.

11. “Rate distortion trade-off for channels with state information,” A.Sutivong and T. Cover, submitted to IEEE International Symposium on Information Theory, Lausanne, Switzerland, June 2002.

12. “Multiple-access channels with state information,” A. Sutivong and T. Cover, submitted to IEEE International Symposium on Information Theory, Lausanne, Switzerland, June 2002.

13. “Degraded broadcast channels with state information,” A. Sutivong, Y. Kim, and T. Cover, submitted to IEEE International Symposium on Information Theory, Lausanne, Switzerland, June 2002.

14. “On the concavity of the increase in entropy in the second law of thermodynamics,” D. Julian and T. Cover, submitted to IEEE International Symposium on Information Theory, Lausanne, Switzerland, June 2002.

15. “Continuum Quantum Rate-Distortion,” T. Berger, Invited seminar, University of Rochester, Rochester, New York, August 20, 2002.

16. “Geometric programming duals of channel capacity and rate distortion,” submitted to IEEE Trans. Info. Theory. Partially presented as “Shannon duality through Lagrange Duality,” M. Chiang and S. Boyd, Allerton Conference 2002.

17. “On the Concavity of the Increase in Entropy in the Second Law of Thermodynamics,” D. Julian and T. Cover, IEEE International Symposium on Information Theory, Yokohama, Japan, June 2003.

11. “Recent progress in quantum Shannon theory,” I. Devetak, seminar presented at Institute for Quantum Information, October 21, 2003.

Quantum Optics Projects

1. "Quantum control via classical orbits," C.R. Stroud, Jr., at Israel Science Foundation Workshop on Quantum Control and Information, Nof Genossar, Israel, November 14-19, 1999.

2. "Quantum control and quantum state measurement," I. A. Walmsley, at Israel Science Foundation Workshop on Quantum Control and Information, Nof Genossar, Israel, November 14-19, 1999.

3. "Quantifying Continuum Entanglement," J.H. Eberly, at Israel Science Foundation Workshop on Quantum Control and Information, Nof Genossar, Israel, November 14-19, 1999.

4. "Quantum control via classical orbits," C.R. Stroud, Jr. at US-Japan Workshop on Coherent Control, Honolulu, HI, December 11-15, 1999.

5. "Engineering entanglement", I.A. Walmsley, at Workshop on Quantum Communications and Information, NEC Research Institute, Princeton, NJ, December 14-16, 1999.

6. “What shape is your photon?” J.H. Eberly, Joint Atomic Physics/ITAMP Colloquium, Harvard University, April 2001.

7. “Propagation and relaxation of entanglement in Heisenberg spin chains,” J. Pratt and J. H. Eberly , Poster paper, Third Cross-Border Workshop on Laser Science, University of Toronto, May 2001.

8. “Qualifying control of photon-atom entanglement in spontaneous emission,” K. W. Chan and J. H. Eberly, Poster paper, Third Cross-Border Workshop on Laser Science, University of Toronto, May 2001.

9. “Fundamental one-photon images,” J.H. Eberly, Invited Talk, International Conference on Squeezed States and Uncertainty Relations, Boston University, June 2001.

10. “Propagation and relaxation of entanglement in Heisenberg spin chains,” J. Pratt and J. H. Eberly, Contributed Paper, International Conference on Quantum Information, University of Rochester, June 2001.

11. “Qualifying control of photon-atom entanglement in spontaneous emission,” K.W. Chan and J.H. Eberly, Contributed Paper, International Conference on Quantum Information, University of Rochester, June 2001.

12. “Control parameter for photon-atom entanglement in spontaneous emission,” K.W. Chan, C.K. Law and J.H. Eberly, Poster Paper, Quantum Optics V, Koscielisko, Poland.

13. “Even stranger than we supposed: from Max Planck to teleportation,” J.H. Eberly, Plenary Invited Talk, AAPT Annual Summer Meeting, July 2001.

14. “Reversible relaxation in quantum optics,” J.H. Eberly, three lectures, Los Alamos Summer School, Los Alamos, NM, July 2001.

15. “Control of photon-atom entanglement and photon wave functions,” K.W. Chan, C.K. Law and J.H. Eberly, Poster Paper, Workshop on Quantum Optics 2001, Jackson, WY, Aug. 2001.

16. “Reverse decoherence - Entanglement arising from quantum noise,” J.H. Eberly, Invited Paper, Conference on Mechanisms for Decoherence - Theory and Applications to Nanotechnology and Quantum Information, Austin, TX.

17. “Quantum information technology of the future?” C.R. Stroud, Jr., invited lecture, Rochester Section, Optical Society of America, November 2001.

18. “Quantum information and quantum computing,” APS-DLS Distinguished Lecture, University of Alabama, May 2001.

19. “Entanglement and Memory-Force Bound States,” J. H. Eberly, ARO-MURI Review, Harvard University, Boston, MA, February 2002.

20. “A New Look at ‘Spooky Action at a Distance’,” J. H. Eberly, Physics Colloquium, Queen’s University, Kingston, Ontario, Canada, March 2002.

21. “Continuum Entanglement Bound States and Quantum Memory Force (QMF),” J. H . Eberly, Invited, Quiprocone Workshop, University of Durham, Durham, UK, April 2002.

22. “Robust vs. Fragile Entanglement and Decoherence vs. Local Dephasing,” J. H. Eberly, Quantum Optics Colloquium, NASA-JPL, Pasadena, CA, May 2002.

23. “Decoherence Control via Random Matrices,” Post-deadline poster, Jin Wang and J. H. Eberly, APS/DAMOP Annual Meeting, Williamsburg, VA, May 2002.

24. “Entanglement Decoherence vs. Local Dephasing, Robust and Fragile Entangled States,” J. H. Eberly, NATO – Advanced Study Institute, Bilkent University, Ankara and Antalya, Turkey, June 2002.

25. “Elementary Introduction to the Schmidt Theorem and Bipartite Entanglement Analysis,” J. H. Eberly, NATO – Advanced Study Institute, Bilkent University, Ankara and Antalya, Turkey, June 2002.

26. “Entanglement in Continuous Hilbert Spaces and The ‘Memory Force’,” J. H. Eberly, NATO – Advanced Study Institute, Bilkent University, Ankara and Antalya, Turkey, June 2002.

27. “Decoherence of Entanglement: A Toy Model,” J. H. Eberly, Poster paper, Perspectives in Decoherence Control and Quantum Computing, Ann Arbor, MI, August 2002.

28. “Information Measure of Available Entanglement in Photon-atom Scattering,” J. H. Eberly, Poster, paper # MK46, K. W. Chan and J. H. Eberly, Laser Science 18, Orlando, FL, September 2002.

29. “Robust and Fragile Entangled Quantum States in a Toy Model,” J. H. Eberly, Poster, paper # ThG2, *Ting Yu and J.H. Eberly, Laser Science 18, Orlando, FL, October 2002.

30. “Schmidt Disentanglement and Quantum Memory Force (QMF),” J. H.Eberly, AMO Physics Seminar, Seoul National University , Seoul, Korea, October 2002.

31. Inaugural Asan Memorial Lectures: “Schmidt Disentanglement and Quantum Memory Force (QMF),” J. H. Eberly, Department of Physics, Korea University, Seoul, Korea, October 2002.

32. “Control of High Entanglement and the EPR Limit,” J. H. Eberly, Invited Hot Topic, Discussion Meeting on Practical Realizations of Quantum Information Processing, The Royal Society, London, November 2002.

33. “Memory Force-a Quantum Tie that Can Bind,” J. H. Eberly, Invited, Symposium on Complexity in Optics, Lorentz Centre, Leiden University, Netherlands, November 2002.

34. “Memory Force and Quantum Entanglement,” J. H. Eberly, Informal AMO Seminar, University of Kaiserslautern, Kaiserslautern, Germany, December 2002.

35. “Quantum Mechanics in the Classical Limit,” C. R. Stroud, Jr., Invited plenary lecture, 38th Conference on the Physics of Quantum Electronics, Snowbird, Utah, January 2002.

36. “Overview MURI Center for Quantum Information,” C. R. Stroud, Jr., MURI Program Review, Harvard University, February 24, 2002.

37. “Technological Importance of Quantum Weirdness,” C. R. Stroud, Jr., Office of Naval Research, Physics Directorate Review, Arlington, VA, May 2002.

38. “Quantum Weirdness: Technology of the Future,” C. R. Stroud, Jr., Invited public lecture, SUNY Binghamton, September 2002.

39. “Rydberg Electron Wave Packets: Observing and manipulating electrons within an atom,” C. R. Stroud, Jr., Physics Colloquium, SUNY Binghamton, September 2002.

40. “Quantum Weirdness: Technology of the Future,” C. R. Stroud, Jr., Invited public lecture, University of Kansas, Lawrence, October 2002.

41. “Rydberg Electron Wave Packets: Observing and manipulating electrons within an atom,” C. R. Stroud, Jr., Physics Colloquium, University of Kansas, Lawrence, October 2002.

42. “Quantum Weirdness: Technology of the Future,” C. R. Stroud, Jr., Invited public lecture, Wichita State University, October 2002.

43. “Rydberg Electron Wave Packets: Observing and manipulating electrons within an atom,” C. R. Stroud, Jr., Physics Colloquium, Wichita State University, October 2002.

44. “Single-query all-optical 50 –element database search,” Ian A. Walmsley, QELS, Baltimore, MD, May 2001.

45. “Engineering entanglement in ultrafast parametric downconversion,” Ian A. Walmsley, ICCSUR, Boston, MA, May 2001.

46. “Single particle quantum computing and the classical limit,” Ian A. Walmsley, Atomic Physics Gordon Conference, Williamstown, MA, June 2001.

47. “Controlling decoherence in molecular vibrational dynamics,” Ian A. Walmsley, Quantum Optics V, Rochester, NY, June 2001.

48. “Controlling decoherence in molecular vibrational dynamics,” Ian A. Walmsley, Quantum Control Gordon Conference, Mt. Holyoke. MA, July 2001.

49. “Resource measures for quantum information processing,” Ian A. Walmsley, ILS-XVI, Long Beach, CA, October 2001.

50. “All-optical 50 –element database search,” Ian A. Walmsley, QUIPROCONE Torino, October 2001.

51. “Taming the Dragon: Closed-loop control of decoherence in molecular vibrations,” Ian A. Walmsley, Quantum Control Workshop, Schloss Ringberg, Bavaria, December, 2001.

52. “Managing photonic entanglement for quantum information processing,” Ian A. Walmsley, QUIPROCONE Workshop, Durham, England, April 2002.

53. “Efficient Generation of Entangled Photons by means of Parametric Downconversion in Controlled Spatio-Temporal Modes,” Ian A. Walmsley, Quantum Communications and Quantum Computation Meeting, Boston, MA, August 2002.

54. “Quantum Information Science,” Ian A. Walmsley, Near Field Optics Conference NFO-7, Rochester, NY, August 2002.

55. “Implementation of the Bernstein-Vazirani algorithm using optics,” Ian A. Walmsley, ICO Conference, Firenze, Italy, September 2002.

56. “Managing Decoherence,” Ian A. Walmsley, ESF /EU Summer School on Coherent Control, Cargese, Corsica, September 2002.

57. “Engineering photons for quantum information processing,” Ian A. Walmsley, Royal Society Meeting on Quantum Information Processing, London, November, 2002.

58. “Engineering photons for quantum information science,” Ian A. Walmsley, Max Planck Insitut für QuantenOptik, Garching, Germany, December 2002.

59. Invited speaker and session chair, Nicholas Bigelow, Institute for the Americas, University of New Mexico Workshop on BEC, February 2002.

60. Invited speaker, Nicholas Bigelow, Department of Physics Colloquium, University of Connecticut, April 2002.

61. Invited speaker, Nicholas Bigelow, Department of Physics Colloquium, University of Florida at Gainesville, April 2002.

62. “Vortex nucleation and arrangement in a stirred Bose-Einstein condensate,” L. O. Baksmaty and N. Bigelow, DAMOP Meeting of the American Physical Society, Williamsburg, VA, May 2002.

63. “Collective excitations of vortex arrays in a trapped Bose-Einstein condensate,” L. O. Baksmaty, S. Woo, and N. Bigelow, DAMOP Meeting of the American Physical Society, Williamsburg, VA, May 2002.

64. “Approaches to BEC in a two-species magnetic trap,” S. B. Weiss, M. J. Banks, J. P. Janis, and N. Bigelow, DAMOP Meeting of the American Physical Society, Williamsburg, VA, May 2002.

65. “Determination of scattering lengths in low-temperature heteronuclear collisions,” S. B. Weiss and N. Bigelow, DAMOP Meeting of the American Physical Society, Williamsburg, VA, May 2002.

66. Recoil effects and BEC,” Nicholas Bigelow, Invited speaker, Gargnano, Italy, June 2002.

67. “Physics of ultracold dilute atomic gasses,” Nicholas Bigelow, Invited speaker, Benasque Center for Science, Benasque, Spain, June 2002.

68. Invited speaker, Nicholas Bigelow, European Workshop on Degenerate Quantum Gasses and Ultraprecise Clocks, Luntern, the Netherlands, September 2002.

69. Invited Seminar, Nicholas Bigelow, Rice University, October 2002.

70. Invited talk, Nicholas Bigelow, Symposium on Chemical Physics and Astronomy, Univ. of Waterloo October 2002.

71. “Quantum Entanglement and EPR States,” J.H. Eberly, Invited Lecture Series, SERC School on Precision Spectroscopy, Indian Institute of Science , Bangalore, India, March 2003.
    Lecture 1: Entanglement Analysis via the Schmidt Theorem
    Lecture 2: Continuous Entanglement and the EPR limit

72. “Quantum Memory, Entanglement and the Schmidt Method of Analysis, “ J.H. Eberly, Physics Seminar, Physical Research Laboratory, Ahmedabad, India, March 2003.

73. “High entanglement and the EPR limit via light scattering,” K.W. Chan, C.K. Law, M.V. Fedorov and J.H. Eberly, Poster Paper, Cross-Border Workshop 2003, University of Waterloo, Waterloo, Canada, May 2003.

74. “Global vs. Local Decoherence of Qubits,” Ting Yu and J.H. Eberly, Poster Paper, 4th European QIPC Workshop, Keble College, Oxford, UK, July 2003.

75. “Routes to Very High Entanglement,” J.H. Eberly, K.W. Chan, C.K. Law and M.V. Fedorov, Poster Paper, 4th European QIPC Workshop, Keble College, Oxford, UK, July 2003.

76. “Transverse quantum Schmidt-mode patterns in down conversion,” J.H. Eberly and C.K. Law, SPIE Annual Meeting, Conference 5161, San Diego, CA, August 2003.

77. “Quantum information and very high entanglement,” J.H. Eberly, K.W. Chan, C.K. Law and M.V. Fedorov, Invited Paper, LPHYS-03, Hamburg University, Hamburg, Germany, August 2003.

78. “Possible Approaches to High Quantum Entanglement and the EPR Limit,” J.H. Eberly, Colloquium, Physics Department, University of Rostock, Rostock, Germany, September 2003.

79. “Possible Approaches to High Quantum Entanglement and the EPR Limit,” J.H. Eberly, Colloquium, Max-Born Institute, Berlin, Germany, September 2003.

80. “Control of Continuum High Entanglement and the EPR Localization Limit in Photon-Atom Scattering,” J.H. Eberly, Invited Paper, Quantum Challenges Conference, Falenty, Poland, September 2003.

81. “Introduction to the Elements of Quantum Information, Bell Inequalities and Teleportation,” J.H. Eberly, Invited Lecture Series, Instituto Nacional de Astrofisica, Optica y Eletronica (INAOE), Puebla, Mexico, September 2003.
    i. Lecture 1: Why Quantum Information is Different
    ii. Lecture 2: Design of Experiments for Bell Inequalities and Teleportation

82. "Nonlinear optics for single photon generation and manipulation", Ian Walmsley, Gordon Conference on Nonlinear Optics, Wolfeboro, NH, July 2003.

83. "Managing Photons for Quantum Technologies", Ian Walmsley, Universität Erlangen, October 2003.

84. "Managing Photons for Quantum Technologies", Ian Walmsley, University of Warsaw, October 2003.

85. “Quantum weirdness in an atom,” C. R. Stroud, Jr., Invited presentation, AAAS Annual meeting Seattle, Washington, February 14, 2004.

86. “The Shape of an Atom,” A. Gondarenko and C. R. Stroud, Jr., NCUR meeting, Provo, Utah, March, 2003.

87. “Collision Properties of Alkali Mixtures and Na-Rb BEC,” S. B. Weiss, M. Bhattacharya, and N. P. Bigelow, DAMOP Meeting of the American Physical Society, Boulder, CO May 2003.

88. “Forbidden Transitions in a Magneto-Optical Trap,” S. B. Weiss, M. Bhattacharya, and N. P. Bigelow, DAMOP Meeting of the American Physical Society, Boulder, CO May 2003.

89. “Understanding Vortex Lattice Dynamics of a BEC,” L. O. Baksmaty, S. J. Woo, S. Choi and N. P. Bigelow, DAMOP Meeting of the American Physical Society, Boulder, CO May 2003.

90. “Continuous variables for discrete photons,” Ian A. Walmsley, Workshop on Continuous Variables Quantum Information Processing, Veilbronn, April 2-5, 2004.

91. “Efficient conditional state preparation of photon number states,” Alfred B. U’Ren, Daryl Achilles, Cezary Sliwa, Christine Silberhorn, Konrad Banaszek, and Ian A. Walmsley, Workshop on Quantum Information Processing with Linear Optics, Erlangen, April 14-16, 2004.

92. “Efficient conditional preparation of single photons for scalable quantum optical networking,” Alfred B. U’Ren, Christine Silberhorn, Konrad Banaszek, and Ian A. Walmsley, Conference on Laser and Electro-Optics / Quantum Electornics and Laser Science Conference CLEO/QELS 2004, San Fransisco, California, Technical digest, IWE4, p. 127, May 16-21, 2004.

93. “Photon number resolving detection using time-multiplexing,” Daryl Achilles, Christine Silberhorn, Alfred B. U’Ren, Cezary Sliwa, Konrad Banaszek, and Ian A. Walmsley,Conference on Laser and Electro-Optics / Quantum Electornics and Laser Science Conference CLEO/QELS 2004, San Fransisco, California, Technical digest, IThD3, p. 139, May 16-21, 2004.

94. “Characterization and preparation of higher photon number states,” Christine Silberhorn, Daryl Achilles, Alfred B. U’Ren, Konrad Banaszek, and Ian A. Walmsley, Conference on Quantum Communication, Measurement and Computing 2004, Glasgow, June 25-28, 2004.

95. “Effcient conditional preparation of single photons for quantum-optical networks,” Alfred B. U'Ren, Christine Silberhorn, Daryl Achilles, Jonathan Ball, Konrad Banaszek, and Ian A. Walmsley, Conference on Quantum Communication, Measurement and Computing 2004, Glasgow, June 25-28, 2004.

96. “Decoherence vs. Disentanglement,” Ting Yu* and J. H. Eberly, Physics Seminar, University of Maryland, College Park, MD, March 2004.

97. “Spontaneous Emission and Finite Disentanglement Times,” J. H. Eberly* and Ting Yu, Invited Lecture, Cross Border Workshop, NRC-Ottawa, Ottawa, Canada, May 2004.

98. “The Phase-Entanglement Trap in EPR Experiments with Massive Particles,” J. H. Eberly, QOLS Seminar, Imperial College, London UK, June 2004.

99. “The Phase-Entanglement Trap in EPR Experiments with Massive Particles,” J. H. Eberly, Institute Seminar, Inst. for Optics, Information and Photonics, Erlangen, Germany, June 2004.

100. “Theory of Observable Phase Entanglement in EPR Experiments with Massive Particles,” J. H. Eberly, QUANTOP Center Seminar, University of Aarhus, Denmark, June 2004.

101. “Theory of Observable Phase Entanglement in EPR Experiments with Massive Particles,” J. H. Eberly, Quantum Optics Seminar, Niels Bohr Institute, Copenhagen, Denmark, June 2004.

102. “Atom-photon entanglement in spontaneous emission,” M. V. Fedorov*, M. A. Efremov, A. E. Kazakov, K. W. Chan, C. K. Law and J. H. Eberly, Contributed paper, International Laser Physics Workshop (LPHYS'04), Modern Trends in Laser Physics Seminar , Trieste, Italy, July 2004.

103. “Going Beyond Bell States with Schmidt,” J. H. Eberly, REU Lecture Series, Los Alamos National laboratory, Los Alamos, NM, July 2004.

104. “Quantum Entanglement and EPR in Continua,” J. H. Eberly, REU Lecture Series, Los Alamos National laboratory, Los Alamos, NM, July 2004.

105. “Quantum weirdness in an atom,” C. R. Stroud, Jr., Invited presentation, AAAS Annual Meeting, Seattle, Washington, February 14, 2004.

106. “Wave packets and coherent control,” C. R. Stroud, Jr., Invited series of five lectures, Rydberg Physics Workshop, Max Planck Institute for Physics of Complex Systems, Dresden, Germany, April 19-23, 2004.

Section 5: Scientific Personnel

Cornell University

Faculty

Dr. Toby Berger, Irwin and Joan Jacobs Professor of Engineering, Electrical and Computer Engineering

Ph.D. Students

Kenneth A. Dennison (Berger; new directions in quantum information processing)
Igor Devetak (Berger; tradeoff problems in quantum information theory)

Harvard University

Faculty

Dr. Charles Marcus, Professor of Physics

Ph.D. Students

Alexander Johnson (Marcus; pulsed and latched detection of quantum states)

University of Rochester

Faculty

Dr. Nicholas Bigelow, Lee A. DuBridge Professor of Physics
Dr. Joseph Eberly, Carnegie Professor of Physics
Dr. Carlos Stroud, Principal Investigator and Professor of Optics
Dr. Ian Walmsley, Professor of Optics

Visiting Faculty

Dr. Ilya Averbukh, Weizman Institute
Dr. C. K. Law, Hong Kong University

Post-Doctoral Associates

Dr. Matthew Anderson
Dr. Konrad Banaszek
Dr. Paolo Bellomo
Dr. Stephen Choi
Dr. Christophe Dorrer
Dr. Michael Fitch
Dr. Chi-Kwong Law
Dr. Jin Wang

Ph.D. Students

Iman Aghilian (Stroud; entanglement of Rydberg atoms in surface MOT)
David Aronstein (revivals and classical-motion bases of quantum wave packets)
Benjamin Brown (Walmsley; coherent control of cold molecular formation)
Kam Wai Clifford Chan (Eberly; Schmidt-mode evolution leading to control of entanglement)
Brian Clader (Eberly;
Luís Eduardo E. de Araujo (Walmsley; quantum control of atoms and molecules)
Filipp Ignatovitch (Stroud;
John Janis (Bigelow; Bose-Einstein condensation)
Anand Jha (Stroud; photon emission in chiral media)
Jan Kleinert (Bigelow;
Alexander Kuzmich (Mandel; non-classical states of atoms an photons)
Mayer Landau (Stroud; entanglement of Rydberg atoms)
Pablo Londero (Walmsley; molecular dimers for quantum information studies)
Alberto Marino (Stroud; entanglement and teleportation of states of matter)
Ashok Muthukrishnan (Stroud; quantum information and computing in multilevel systems)

Hideomi Nihira (Stroud; entanglement in three-level fluorescence)
Eric Page (Bigelow; dispersion management for applications in optical links for entanglement channels)
Jose Gandarias Perillan (
Jeffrey S. Pratt (Eberly; spin-network entanglement and entanglement transfer)
Michaela Tscherneck (Bigelow; quantum information)
Alfred U'Ren Cortes (Walmsley; engineering entanglement using quasi phase matched nonlinear waveguides)
Weiss, Stanley Benjamin (Bigelow; laser cooled atoms and molecules)
Sung Jong Woo (Bigelow; quantum information)
York E. Young (Bigelow; cold collisions of laser cooled Na and Rb atoms)

Undergraduate Students

Alexander Gondarenko

Rutgers University

Faculty

Dr. Michael Gershenson, Professor of Physics and Astronomy
Dr. Sergei Sysoev, Research Associate, Physics and Astronomy

Ph.D. Students

Vitaly Podzorov (Gershenson; quantum information)

Stanford University

Faculty

Dr. Thomas Cover, Kwoh-Ting Li Professor of Electrical Engineering and Statistics
Dr. Gleb Klimovitch
Dr. Martin Morf
Dr. Yoshihisa Yamamoto, Professor of Electrical Engineering and Applied Physics

Post-Doctoral Associates

Dr. Patrik Recher

Ph.D. Students:

David Julian (Cover; information theory and ulaity of the theory of data compression)
Na Young Kim (Yamamoto; electron entanglement)
William Oliver (Yamamoto; information theory and quantum information)
Jon Yard (Cover; information theory in quantum information)
Assaf Zeevi (Cover; quantum key distribution)

Section 6: Degrees Earned and Ph.D. Thesis Abstracts

List of Ph.D. Degrees

Condensed Matter (Gerhsenson, Marcus, Yamamoto)

1. "Coherence, charging, and spin effects in quantum dots and quantum point contacts," Sara M. Cronenwett, Stanford University; Prof. Charles Marcus, Thesis Advisor; December 2001

2. "The generation and detection of electron entanglement," William D. Oliver, Stanford University; Prof. Yoshihisa Yamamoto, Thesis Advisor; August 2002

Information Theory (Berger, Cover)

1. "Tradeoff problems in quantum information theory," Igor Devetak, Cornell University; Prof. Toby Berger, Thesis Advisor; January 2002

2. "Channel capacity and state estimation for state-dependent channels," Arak Sutivong, Stanford University (partially supported); Prof. Thomas Cover, Thesis Advisor; March 2003

3. "Solving nonlinear problems in communication systems using geometric programming and dualities," Mung Chiang, Stanford University (partially supported); Prof. Thomas Cover, Thesis Advisor; August 2003

4. "Capacity of erasure networks," David Julian, Stanford University; Prof. Thomas Cover, Thesis Advisor; September 2003

5. "Simultaneous classical-quantum capacities of quantum multiple access channels," Jon Yard, Ph.D. thesis,; Stanford University; Prof. Thomas Cover, Thesis Advisor; March 2005

Quantum Optics (Bigelow, Eberly, Stroud, Walmsley)

1. "Investigation of non-classical states of atoms and photons," Alexander M. Kuzmich, University of Rochester; Prof. Leonard Mandel, Thesis Advisor; December 1999

2. "Cold collisions of laser cooled Na and Rb atoms," York E. Young, University of Rochester; Prof. Nicholas Bigelow, Advisor; March 2001

3. "Quantum information and computing in multilevel systems," Ashok Muthukrishnan, University of Rochester; Prof. Carlos Stroud, Thesis Advisor; December 2001

4. "Quantum control of atoms and molecules," Luís Eduardo E. de Araujo, University of Rochester; Prof. Ian Walmsley, Thesis Advisor; 2001

5. "Revivals and classical-motion bases of quantum wave packets," David L. Aronstein, University of Rochester; Prof. Carlos Stroud, Thesis Advisor; September 2002.

6. "Laser cooled atoms and molecules: Prospects for a sodium-rubidium Bose-Einstein condensate," Stanley B. Weiss, IV, University of Rochester; Prof. Nicholas Bigelow,

Thesis Advisor; February 2004

7. "Multi-photon state engineering for quantum information processing applications," Alfred U'Ren, University of Rochester; Prof. Ian Walmsley, Thesis Advisor; May 2004

8. "Building a Bose-Einstein condensation experiment in ^{87}Rb," John P. Janis, University of Rochester; Prof. Nicholas Bigelow, Thesis Advisor; August 2004

9. "Entanglement in quantum spin systems," Jeffrey S. Pratt, University of Rochester; Prof. Joseph Eberly, Thesis Advisor; April 2005

10. "Two-particle breakup and Einstein-Podolsky-Rosen entanglement," Kam Wai Clifford Chan, University of Rochester; Prof. Joseph Eberly, Thesis Advisor; April 2005

Coherence, Charging, and Spin Effects in Quantum Dots and Point Contacts

Sara Marie Cronenwett
Stanford University

Thesis Advisor: Professor Charles Marcus
December 2001

Abstract

A series of experiments is presented on electron transport through quantum dots and quantum point contacts in the strong-tunneling regime where electron coherence, charging, and spin play significant roles. In the first experiment, transport measurements are presented for quantum dots in the strong-tunneling Coulomb blockade (CB) regime. Fluctuations of the conductance, evidence of quantum interference, show sensitivity to charging effects in the CB valleys where elastic cotunneling is the dorninent transport mechanism. The effects of interactions are accounted for using a single parameter—the charging energy (the energy required to add an additional electron to the dot)—and are measured using the magnetic field correlation length of conductance fluctuations. The second experiment shows CB in a quantum dot with one fully-transmitting lead and one weak-tunneling lead. In this system, the CB appears only due to constructive interference of backscattered trajectories. The predominant effect of interactions, namely the Coulomb blockade, is turned on and off by quantum interference. The third and fourth experiments investigate the Kondo effect, a classic many-body problem where the effects of coherence and interactions cannot be trivially separated. Quantum dots are well suited to study the Kondo effect as many parameters can be varied in dots that cannot be changed in traditional bulk metal systems. The second observation of the Kondo effect in dots is presented here, including the first demonstration of a gate voltage controlled Kondo temperature. The last part of this dissertation describes quantum point contacts (QPCs) which show a number of remarkable similarities to the Kondo effect in dots. Transport measurements of the "0.7 structure", a robust extra plateau or shoulder-like feature in the lowest mode of a QPC, show evidence for a lifted spin-degeneracy. The formation of a zero-bias peak at low temperature, the collapse of the temperature-dependent conductance to a single curve when scaled by one parameter (the Kondo temperature), and the correspondence of this temperature scaling parameter to the source-drain bias voltage width of the zero-bias peak strongly suggest that a Kondo-like correlated many-electron state forms in the QPC at low temperatures. This suggestion is currently under discussion theoretically.

The Generation and Detection of Electron Entanglement

William David Oliver
Stanford University

Thesis Advisor: Professor Yoshihisa Yamamoto
January 2003

Abstract

Hanbury Brown and Twiss demonstrated the quantum phenomenon known as "photon bunching" in 1956 using a second-order photon intensity correlation technique, opening the field of photon quantum optics. The study of higher-order correlation functions in photon and atom-cavity systems has subsequently led to a more complete understanding of the quantum statistical and quantum mechanical phenomena resulting from quantum entanglement. With the development of two-dimensional electron gas substrates and nanofabrication techniques, it is now also feasible to consider electron quantum optics, the investigation of higher-order current-correlation functions of electrons and composite particles in mesoscopic devices at cryogenic temperatures.

This thesis embodies two general subjects: 1) the generation of electron entanglement, and 2) the detection of electron entanglement. The work can be primarily classified into two experimental and three theoretical efforts. First is the experimental demonstration of "electron anti-bunching" using a Hanbury Brown and Twiss-type intensity interferometer. The electron intensity interferometer and its partner, the electron collision analyzer, constitute an electron quantum optics toolbox that is used to characterize single-electron states and sources. Second is the use of the quantum optics toolbox to experimentally demonstrate and investigate noise suppression at the 0.7 and, more generally, *n.m* conductance anomalies in quantum point contacts. This noise suppression is strong evidence that a deterministic splitting and, consequently, a natural regulation of the electron flow occurs in quantum point contacts biased to feature conductances away from the integer quantum units. In many cases, deterministic splitting is beyond a single particle picture and, in those cases, may be considered to be a nonlinear effect. Nonlinear deterministic splitting is a necessary, although insufficient, requirement of an electron entangler.

The extension of the quantum optics toolbox to states and sources of arbitrary quantum statistics comprises the third work. An electron bunching/anti-bunching experiment is proposed as a Bell-state analyzer for Einstein-Podolsky-Rosen-type two-electron entanglement. Fourth is the theoretical proposal of a quantum dot entangler, a device that generates entangled-electron spin-singlet states. The device illustrates the general property of Coulomb-mediated four-wave mixing with electron waves. It provides another example of nonlineax deterministic splitting; in this case, the nonlinearity is the Coulomb interaction. Fifth is the extension of the Landauer-Büttiker coherent scattering formalism to include the Rashba spin-orbit coupling effect. This formalism is used to characterize the effect that spin-orbit coupling may have on electron quantum optics experiments in two-dimensional electron gas systems.

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William David Oliver
Stanford University

Thesis Advisor: Professor Yoshihisa Yamamoto
January 2003

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The extension of the quantum optics toolbox to states and sources of arbitrary quantum statistics comprises the third work. An electron bunching/anti-bunching experiment is proposed as a Bell-state analyzer for Einstein-Podolsky-Rosen-type two-electron entanglement. Fourth is the theoretical proposal of a quantum dot entangler, a device that generates entangled-electron spin-singlet states. The device illustrates the general property of Coulomb-mediated four-wave mixing with electron waves. It provides another example of nonlineax deterministic splitting; in this case, the nonlinearity is the Coulomb interaction. Fifth is the extension of the Landauer-Büttiker coherent scattering formalism to include the Rashba spin-orbit coupling effect. This formalism is used to characterize the effect that spin-orbit coupling may have on electron quantum optics experiments in two-dimensional electron gas systems.

Tradeoff Problems in Quantum Information Theory

Igor Devetak
Cornell University

Thesis Advisor: Professor Toby Berger
January 2002

Abstract

In this thesis two tradeoff problems of quantum information theory are presented. One is a generalization of rate-distortion theory to quantum information processing. The exact quantum rate-distortion function is found for independent, identically distributed qubit sources and a particular distortion measure under the condition of unrestricted classical side information. The other is the tradeoff between entanglement and classical communication needed for asymptotically perfect remote preparation of pure qubit states. The optimal low-entanglement tradeoff curve is found when restricted to teleportation based protocols. Conditional bounds are obtained for the high entanglement region.

Capacity of Erasure Networks

David Julian
Stanford University

Thesis Advisor: Professor Thomas M. Cover
2004

Abstract

Consider an ad-hoc network where links are created and destroyed as nodes move about and turn on and off. Alternatively, consider a packet loss network where packets along hops are dropped due to queueing buffer overflows. Finally, consider a wireless network in a battlefield where links and nodes are setup and destroyed. We are interested in the effect of these dynamic aspects of link creation and destruction on the network capacity region. To explore the dynamic effects we model the network without the dynamic aspects as a static underlying network, and account for the dynamic aspects as link erasures. This model is made precise, and the erasure channel capacity region C and coding strategy is compared to the underlying channel capacity region C and coding strategy for several network topologies. Also, erasure process dependencies in time and space are explored. For many families of networks, the erasure network capacity region $\tilde{C}$ is the underlying network capacity region C scaled by the probability that an erasure does not occur. Further, the erasures channel capacity-achieving distribution is the same as the underlying channel capacity-achieving distribution; thus the underlying channel random codebook can be used for the erasure channel, but with proportionally fewer codewords. Finally, through examples it is seen that the relationship $C = \alpha C$ does not hold in general, but that a cut-sets bound relationship does hold under an independent noise assumption.

Simultaneous Classical-Quantum Capacities of Quantum Multiple Access Channels

Jon Thomas Yard
Stanford University
2005

Thesis Adviser: Professor Thomas M. Cover

Abstract

I analyze quantum channels with two senders and a single receiver, used in a variety of ways for the simultaneous transmission of classical and quantum information. Suppose that two independent senders, Alice and Bob, have access to different parts of the input of an arbitrary quantum channel with a single receiver Charlie. By invoking existing coding theorems for single-user channels, I prove two theorems which partially characterize the rates at which Alice and Bob can simultaneously transmit independent classical and quantum information to Charlie. The first theorem offers a multi-letter characterization of the classical-quantum capacity region, which consists of the rates at which it is possible for Alice to send classical information while Bob sends quantum information. The second theorem gives a multi-letter characterization of the quantum-quantum capacity region, which is comprised of the rates at which Alice and Bob can each send quantum information. As an application, for each situation I introduce a channel for which the associated region is provably single-letter and describable via a simple analytic expression. Finally, I mention another characterization of the classical-quantum region, concluding with a description of the full four-dimensional region of rates at which both senders can simultaneously send classical and quantum information.

Investigation of Non-Classical States of Atoms and Photons

Alexander M. Kuzrnich
University of Rochester
1999

Thesis Advisor: Professor Leonard Mandel

Abstract

This dissertation deals with theoretical and experimental research on non-classical, or entangled, states of atoms and photons.

In the first part, I describe two approaches to the preparation of entangled states of a large number of atoms. The first approach is based on the transfer of quantum correlations from non-classical light to the atomic spins. I consider three different situations: (a) the atoms are placed in a loss-free cavity and no relaxation of any kind is present; (b) the atoms are placed in a cavity with input and output for the electromagnetic field and the atoms spontaneously decay from the upper state; (c) there is no cavity around the atoms and spontaneous emission is present. I show that in all three situations with judicious choice of parameters, entangled samples of atoms can be produced. The second approach is based on quantum-nondemolition (QND) measurements of collective atomic operators. I describe experiments with pulsed and cw light as the probe, that result in squeezed spin states of atoms. When a rf magnetic field is applied to the atomic sample, sub-shot noise performance of an atomic spin interferometer is demonstrated.

In the second part of the thesis I describe investigations of phase properties of two-photon and single-photon states. These experiments make use of spontaneous type-I1 down-conversion in a nonlinear crystal. First, interferometric measurement of a phase shift at the Heisenberg limit for a two-photon state is described. Next, a violation of Bell-type inequalities in phase space is demonstrated for the quantum optical version of the Einstein-Podolsky-Rosen state. Finally, some recent work directed toward homodyning a single photon against a strong local oscillator field is described.

Quantum Information and Computing in Multilevel Systems

Ashok Muthukrishnan
University of Rochester

Thesis Advisor: Professor Carlos Stroud
December 2001

Abstract

We have studied the extension of the new field of quantum computing to the multilevel domain, where the information is stored in a coherent superposition of more than two levels. Interference and entanglement, the hallmarks of quantum mechanics, are more strikingly present in a multilevel system, in the form of wave packets and decoherence. This thesis explores new tools and applications for multilevel quantum information processing in Rydberg atoms.

The quantum equivalent of a classical bit is a qubit, a two-level system. Quantum computational logic involves conditional unitary transforms on two qubits, which are the quantum analogs of logic gates in classical computer science. The multilevel extension of a qubit is a qudit, a *d*-level quantum system. We present several programs for universal quantum logic involving audits, and physically motivate the formalism with examples from quantum control.

Wave packets arise from multilevel quantum interference, and they give an interesting new perspective on quantum information stored in a multilevel system. We show that an alternative realization of a qudit in a quantum system is a set of *d* wave-packet states that are physically separated in time. The wavepacket basis is connected to the energy-level basis by a Fourier transform, a key ingredient of quantum algorithms. We apply these ideas to Rydberg atoms, and show that an appropriate coupling between such atoms enables a conceptually simpler implementation of the quantum version of the Fast Fourier transform algorithm.

Lastly we explore atomic angular momentum as a computational observable. Most of the states in the hydrogen atom are degenerate in energy but differ by discrete units of angular momentum. We show that using Laguerre-Gaussian laser modes, which possess orbital field angular momentum, these internal angular momentum states in the atom can be entangled with its quantized center-of-mass angular momentum. We propose this entanglement as the building block for multilevel quantum computing using angular-momentum states.

Quantum Control of Atoms and Molecules

Luís Eduardo E. de Araujo
University of Rochester

Thesis Advisor: Professor Ian Walmlsey
2000

Abstract

In this thesis, we introduce a different, and simple approach to controlling quantum systems. We show that the quantum-control problem can be greatly simplified by simply limiting the duration of the driving force to less than one characteristic period of the system (for an atomic-electron Rydberg wave packet this would be the Kepler period, for example, or the vibrational period in the case of a molecule). If the target state is a bound state of the system, than for times less than the characteristic period, the particle does not have the opportunity to reach the system's boundary, and acts essentially as a classical free particle. Such a restriction on the duration of the driving field allows an analytic solution to be found, even in the nonperturbative regime. This analytic solution helps clarify some of the differences between the perturbation and the nonperturbative regimes of excitation. We also show that our solution is nonunique, and the quantum controller has a multiplicity of solutions to chose from.

We will discuss the technique with respect to the hydrogen atom and diatomic molecules, but it can be readily extended to a variety of systems consisting of a lower and an upper manifold of eigenstates.

In particular to the case of molecules, in the nonperturbative regime, population may get trapped in the lower manifold due to the large bandwidth of the exciting pulse. We show that population trapping is avoided by choosing among the many possible solutions one with the longest possible duration, and yet, shorter than the vibrational period of the system.

The validity of our solution is tested by comparison with a direct numerical integration of Schrödinger's equation, and it is found to yield the target state and population transfer with very high accuracy in both regimes of excitation.

We also report on the experimental detection of cold molecules, formed in a magneto-optical trap, with ultrashort-optical pulses.

Revivals and Classical-Motion Basis of Quantum Wave Packets

David L. Aronstein
University of Rochester

Thesis Advisor: Professor Carlos Stroud
September 2002

Abstract

This thesis explores the boundary between classical and quantum mechanics by studying wave packets, coherent superpositions of the stationary states of a quantum system. Such wave packets travel as localized entities along the trajectories predicted by classical mechanics for small windows of time before they spread out and decav away. Our investigations focus on two central issues — the revivals of the shape and classical motion of these wave packets that occur long after their initial decay, and the classical-motion bases that describe the quantum wavefunction in terms of constitutive objects that move classically.

We study the infinite square-well potential. a simple model of complete confinement in a one-dimensional interval. The quantum motion seen in this potential is compared with classical models of a particle bouncing between two walls and of a wave traveling along a stretched string with both ends secured. We uncover a remarkable *wave-motion basis*. with which the wavefunction at any moment in time can be decomposed into a sum of distinct wave propagations of the initial *quantum* wavefunction in the *classical* wave equation. These results are extended to the finite square-well potential and we show how the wave-motion basis can be reconciled with the seemingly disparate theory of revivals for highly excited quantum wave packets.

We explore the commonalities of the quantum revivals seen in a wide variety of systems by developing a mathematical formalism called *phase-difference equations*. These equations connect physical models for revivals with the subsequent prediction of revival times in a general way and offer a comprehensive "calculus"' for understanding revival phenomena. We apply this calculation to several examples to demonstrate its power and versatility.

Using a recently developed semiclassical basis for quantum states, we explore the radial wave packets of the hydrogen atom. Viewed in the semiclassical basis, the revivals of these wave packets are shown to arise from constructive interference among groups of classical particles on neighboring tracks of a Lagrange manifold in phase space, in a way that parallels the interference among the discrete stationary states found in the standard view of revivals.

Laser Cooled Atoms and Molecules:
Prospects for a Sodium-Rubidium Bose-Enstein Condensate

Stanley Benjamin Weiss IV
University of Rochester
2004

Thesis Advisor: Professor Nicholas P. Bigelow

Abstract

Since the discovery of Bose-Einstein Condensation (BEC) in 1995, the physics of quantum-degenerate gases has received a great deal of attention. In recent years, multi-component quantum-degenerate gases, including two-species BECs (TBECs), spinor BECs, and Fermi-BEC mixtures have been investigated. In this thesis, experimental and theoretical work aimed at creating and understanding a sodium-rubidium (Na-Rb) TBEC is presented. We have constructed a laser cooling and trapping apparatus designed to simultaneously Bose-condense both rubidium and sodium atoms. Recent experiments on evaporatively cooled rubidium-87 are discussed. A calculation of the Na-Rb interspecies scattering lengths is reported, and we assess the prospects of producing a stable TBEC in the Na-Rb system.

Multi-Photon State Engineering for Quantum Information Processing Applications

Alfred B. U'Ren
University of Rochester

Thesis Advisor: Professor Ian Walmsley
May 2004

Abstract

In this thesis we study the development of parametric downconversion (PDC) sources tailored for specific applications within the field of quantum information processing. We study the relationship between the modal properties of photon pairs and their performance in a number of experimental situations taken from the current literature in quantum optics. We derive specific conditions that such a modal structure must satisfy in order for ideal performance to be guaranteed in each type of experiment. In particular, we show that two photon states exhibiting spectral/temporal factorizability lead to Fourier transform limited conditionally-prepared single-photon wavepackets described by a quantum mechanically pure state. Such states are important in the context of interferometry experiments relying on more than one PDC source. Experimental techniques designed to realize such factorizable states are presented. In particular, we present the design of a photon-pair source based on ultrafast-pumped type-II PDC from a KDP crystal which is expected to emit photon pairs exhibiting such factorizabi1ity.

We report the experimental demonstration of a novel source of conditionally-prepared single photons based on a quasi-phase matched type-II parametric down conversion (PDC) in a micro-structured waveguide in conjunction with an ultra short pulsed pump. Our source exhibits several key advantages: i) Emission in well-defined modes. which significantly enhances photon collection efficiencies and permits high-visibility interference between single photons from distinct sources. ii) Type-II operation yields orthogonally polarized photon pairs, easily split by polarization. iii) The ultrashort pump yields precise timing, paving the road towards the concatenation of multiple waveguides. iv) Fiber-coupling of the conditionally prepared single photons means that such photons can be readily used in fiber-based quantum networking. Our source exhibits an extraordinarily high brightness coupled with a remarkably high conditional detection efficiency, and was shown to produce frequency-tunable single photons in the range 720-850nm. We present the violation of a Cauchy-Schwarz classical inequality, proving the non-classical nature of the correlations employed for conditional preparation of single photons.

Building a Bose-Einstein Condensation Experiment in ^{87}Rb

John P. Janis
University of Rochester
2004

Thesis Advisor: Professor Nicholas P. Bigelow

Abstract

Bose-Einstein condensates offer an opportunity to study quantum mechanics on a large scale. To do this, we have constructed an experimental apparatus capable of creating a Bose-Einstein in ^{87}Rb. We have built a double MOT loaded magnetic trapping system which can trap and cool more than a billion atoms. Through the use of forced rf evaporation, we have cooled the trapped atoms to temperatures as low as 750nK and phase space densities of ~0.5. In addition, we have modeled a new Sisyphus cooling technique with predicted efficiencies of $\alpha >$ 3 down to temperatures of 25μK. This new cooling scheme predicts a factor of ten improvement in condensed atom number over rf evaporation alone.

Entanglement in Quantum Spin Systems

Jeffrey Scott Pratt
University of Rochester
2005

Thesis Advisor: Professor Joseph H. Eberly

Abstract

This thesis analyzes entanglement in systems of interacting quantum spins. Heisenberg spin graphs, consisting of exchange-coupled two-level systems, are introduced as an appropriate setting for the study of both natural spin systems, such as magnets, and artificial spin systems, such as qubit arrays in quantum computers. Static entanglement in both eigenstates and thermal states, as well as dynamical entanglement evolution from localized excitation states, are examined in a variety of Heisenberg spin graphs, with a particular focus on the Heisenberg spin chain. Isotropic ferromagnets are shown to possess a universal low-temperature density matrix which precludes pairwise entanglement between spins. The mechanism of entanglement cancellation is investigated, revealing a core of states resistant to pairwise entanglement cancellation. Numerical studies of one-, two-, and three-dimensional lattices as well as irregular geometries showed no pairwise spin entanglement in ferromagnets at any temperature or magnetic field strength. The effects of weak Ising and Dzyaloshinski-Moriya anisotropies on spin entanglement are explored. The qubit entanglement induced by quasiparticle excitations in the Heisenberg spin chain and its relationship to the Bethe Ansatz structure of the eigenmodes is studied. A phenomenon called entanglement quenching, which suppresses eigenstate entanglement, is described and shown to be mediated by Goldstone magnons. The contrasting entanglement structures of scattering and bound states are characterized. Finally, dynamical entanglement phenomena are studied. A Heisenberg spin graph can be viewed as either as a quantum logic or memory register embedded in an environment causing deterministic decoherence, or as a passive quantum network for the exchange of quantum information. The generation, transport, and decay of entanglement in Heisenberg spin chains is examined, and an intuitive physical picture of a polarized excitation current mediating entanglement dynamics is developed.

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Section 7: Report of Inventions

Patent application: 60/438,769 "Efficient Room-Temperature Source of Polarized Single Photons," S. Lukishova, R. W. Boyd, and C. R. Stroud, Jr., January 2004.

Section 8: Technology Transfer

8.1 Center for Quantum Information Website

The CQI website provides an Overview of the Center as well as information on personnel, publications (links provided), links to other universities involved in the Center, and details on seminars and meetings sponsored by the Center.

www.optics.rochester.edu:8080/~stroud/cqi.

8.2 Center Sponsorship of Workshops and Conferences

Workshop on Fundamental Issues in Quantum Information (1999)

An expert challenge workshop was held at the University of Rochester on October 29-31, 1999, sponsored by the U.S. Army Research Office and the MURI Center for Quantum Information. The purpose of this workshop was to identify some of the most important open foundational questions in quantum information science, and subsequently to identify ways in which the CQI faculty could address them.

The workshop format was slightly unusual in that each of the experts were asked to directly address the following challenge: To identify for the audience during their presentation a specific issue of set of issues that is not currently getting the attention it deserves. The set of identified issues need not have been something upon which the expert was currently working, but might have been an old question that needs re-examination, and perhaps a re-evaluation in importance, or a problem that they believed may become a critical one in the near future.

First International Conference on Quantum Information (ICQI) (2001)

The MURI Center for Quantum Information was a co-sponsor of the First International Conference on Quantum Information (ICQI) held at the University of Rochester on June 10-13, 2001. It was co-sponsored by the Optical Society of America and was held in co-location with the Eighth Rochester Conference on Coherence and Quantum Optics (CQ08). The conference covered all aspects of quantum information and science, including various implementations of computing, communications and cryptography, and applications as well as theoretical aspects of the subject.

The conference format was such as to encourage both pedagogy and frank discussions of the leading research in the field. One-hour long plenary tutorials were planned to cover the main sub-disciplines, as well as a liberal selection of one-half hour invited talks on current research problems from outstanding researchers in the field.

Cross Border Workshop on Quantum Correlation and Nonlinear Photon Physics (2002)

The Cross-Border Workshop is held annually bringing together scientists working in atomic, molecular, and optical science and engineering from around the Great Lakes region (Canada and United States). The workshop allows graduate students and post-docs to present their research and interact with scientists in an informal setting. The 2002 Annual Cross Border Workshop was held at the University of Rochester on May 24-26 2002. Sixty students, professors, and researchers from universities and research laboratories gathered for three days on the University of Rochester campus to hear a series of tutorials and review current research interests. The 2002 Workshop was jointly sponsored by the MURI Center for Quantum Information and the Rochsester Theory Center. The theme for 2002 focused on Quantum Correlation and Nonlinear Photon Physics. A sampling of research topics included: ultrafast and strong-field physics, quantum information, and nonlinear and fiber optics.

8.3 Graduate Courses on Quantum Information

The research result output from the MURI program has generated several area specific courses for graduate students.

Stanford University

Dr. Yoshihisa Yamamoto, Professor, offered several one-quarter graduate level courses on quantum information. He provides lecture notes and problem sets as course material. Below are the course descriptions as they appear in the Stanford Graduate Bulletin:

APPPHYS226. Physics of Quantum Information — Review of basic laws and concepts of quantum information science. Fundamental postulates of quantum mechanics: symmetrization postulate, quantum indistinguishability and multi-particle interference, commutation relation and quantum measurement, reduction postulate and impossibility of measuring, cloning and deleting a single wavefunction. Quantum information theory: von Neumann entropy, Holevo information and Schumacher data compression. Decoherence: Lindbladian, quantum error correction, and purification of entanglement. 3 units

APPPHYS227. Application of Quantum Information — Review of concepts and constituent technologies of quantum information systems. Quantum cryptography: single photon and entangled photon-pair-based quantum key distributions, quantum teleportation, quantum repeater. Quantum computer: Deutsch-Josza algorithm, Grover algorithm, Shor algorithm, quantum simulation, quantum circuits. Quantum hardwares: atomic physics, nuclear magnetic resonance, spintronics and quantum optics. 3units

APPPHYS388. Mesoscopic Physics and Nanostructures — Optical properties of semiconductor nanostructures: interband and intraband optical transitions, excitons and polaritons, semiconductor Bloch equations, bosonization, exciton BEC, exciton laser. Transport properties in mesoscopic and atomic systems: electron optics vs. photon optics, Landauer-Buttiker formula, noise in diffusive and dissipative transport, nonequilibrium Green's function, electron entanglement Coulomb blockade, single electronics, and spin dynamics in semiconductor quantum dots. . Partly Journal Club format with presentations by students on assigned topics. 3 units

University of Rochester

During the Spring 2003 semester, the Center for Quantum Information is hosting a series of tutorial lectures on the subject of "Physics of Matter Waves" by Professor Kasimir Rzazewski, Center for Theoretical Physics, Polish Academy of Sciences, Warsaw, Poland. Students attending these lectures will receive credit through OPT 592 Special Topics in Quantum Information. The lectures are proving valuable in educating the whole quantum optics community about an important area that is not currently covered in our regular curriculum. Both faculty and graduate students are attending this popular series, with the audience attendance averaging 30 person per lecture.

8.4 Public Lectures

Members of the Center have given several lectures to acquaint the public with the field of quantum information.

Professor Joseph H. Eberly (University of Rochester)

Invited by the Friends of the Rochester Public Library to speak to attendees of their regular Evening Lecture Series called Thursday Thinkers. The title to which he was asked to respond was "Beam Me Up Scotty - The New World of Quantum Physics." Speaking in layman's terms, Prof. Eberly's talk traced highlights in the evolution of quantum physics: from Planck's introduction of a new universal constant to explain blackbody radiation, through Einstein's inspired creation of stimulated emission, to his doubts about quantum theory, as expressed in the famous EPR paper. The roles of Bohm, Bell, Clauser and Mandel in resolving the "EPR paradox" were mentioned and the process of teleportation described semi-technically. His half-hour talk generated over an hour's worth of "questions and answers."

Presented three lectures on entanglement in quantum information at the NATO – Advanced Study Institute, Bilkent University, Ankara and Antalya, Turkey, June 2002.

"Entanglement Decoherence vs. Local Dephasing, Robust and Fragile Entangled States"

"Elementary Introduction to the Schmidt Theorem and Bipartite Entanglement Analysis"

"Entanglement in Continuous Hilbert Spaces and The 'Memory Force'"

Professor Carlos R. Stroud, Jr. (University of Rochester)

Gave a lecture to industrial scientists at the Rochester Section – Optical Society of America entitled "Quantum Information: Technology of the Future," November 2001. Prof. Stroud also gave lectures on this topic to general audiences at the University of Alabama and Truman State University as part of the Distinguished Travelling Lecturer Program of the Division of Atomic, Molecular and Atomic Physics of the American Physical Society. These lectures were presented in May 2001.

Presented public lectures on "Quantum Weirdness: Technology of the Future?" at SUNY Binghamton, the University of Kansas, and Wichita State University. Attendance at the lectures by the general public was substantial, with more than 300 in Lawrence, Kansas for an evening lecture.

8.5 Quantum Optics Teaching Laboratory

To attract young scientists to the field of quantum information and to give them the tools and understanding to pursue it, a new laboratory was created, the Quantum Optics Teaching Laboratory at the University of Rochester. This is an interdepartmental laboratory between the Department of Physics and Astronomy and The Institute of Optics. A laboratory course will be offered that will introduce both optical engineering and physics undergraduate students to the basic concepts and tools of this new discipline. The goal of the project is to develop a set of interdisciplinary laboratory experiments in the field of Quantum Information. During the 2003 summer, two summer students worked on this project. Current experimental setups (Fig. 1) include three teaching laboratory experiments with written manuals: (1) Entanglement and Bell's inequalities (Fig.1, right); (2) Single photon interference in a Mach-Zehnder interferometer; (3) Young's double slit experiment with single photons. In the future, we are planning two additional teaching laboratory experiments on quantum information (single photon source using single molecule fluorescence in liquid crystal hosts, and quantum cryptography) to prepare undergraduate and graduate students for the age of quantum information.

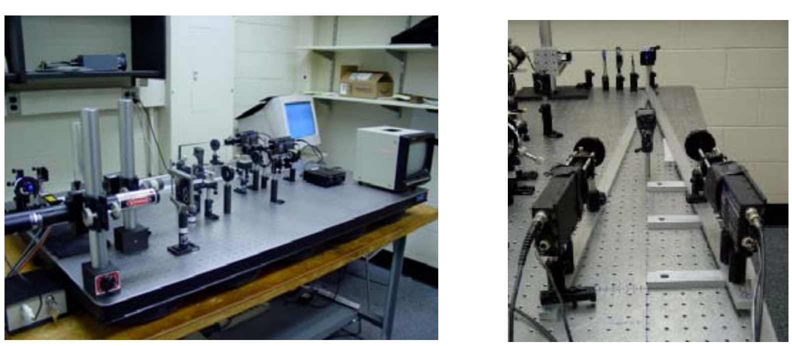

Fig. 1. Quantum optics teaching laboratory setups.